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## ABSTRACT

[1] Accurate estimates of storm surge magnitude and frequency are essential to coastal flood risk studies; however uncertainty within such calculations for the Bay of Bengal is poorly understood. We use the IBTrACs dataset to estimate natural variability in five key parameters used to describe an idealized cyclone, and create a set of idealized but equally likely "1 in 50 year" recurrence interval cyclone events. Each idealized cyclone is then used to force a storm surge model giving predicted peak water-levels along the northern Bay of Bengal coast. Finally, this extreme water level uncertainty is propagated through a hydrodynamic inundation model to predict flood extent and depth over inland coastal floodplains. The descriptive parameters of the most extreme cyclones showed no dependence on their landfall location which allows us to pool characteristics for the entire Bay of Bengal. Instead we find the variability of cyclone parameters translates into large uncertainty for coastal inundation, which must be considered for flood risk management decisions.

## 1. INTRODUCTION

[2] Flood risk from tropical cyclone storm surge is high in the northern Bay of Bengal, and projected to increase with sea-level rise (see Karim and Mimura, 2008). Several hydrodynamic models have been developed to simulate storm surges in the Bay of Bengal (e.g. Flather, 1994), which are typically forced with wind and pressure fields from an idealised cyclone model (e.g. Jelesnianski and Taylor, 1973). One successful example that has shown predictive skill is the IIT-D (Indian Institute of Technology – Delhi) storm surge model (see Dube et al., 2009), which is used as part of an early warning system (Dube et al., 1994) and credited with reducing loss of life in the 2007 Cyclone *Sidr* flooding event (Paul, 2009). Cyclone *Sidr* was a category IV storm that made landfall on the Bangladesh coastline (at 89.8°E) on the 15$^{th}$ November 2007, resulting in a 5.8m surge which, despite the efforts of forecasters, left 3406 people dead and caused damage totalling US$1.7 Billion (Paul, 2009; Dube et al., 2009). To further reduce storm surge fatalities in Bangladesh, improved coastal flood risk estimates are a priority, and this demands the accurate estimation of storm surge magnitude and frequency.

[3] In the Bay of Bengal, a lack of high quality water-level records with which to estimate extreme water-levels and their recurrence interval, has led previous storm surge flood hazard studies to estimate extreme water-levels from more available wind speed data (e.g. Chowdhury et al., 1998). More recently, extreme water-level estimates have been produced for the East Indian coastline by extrapolating cyclone parameters from an observations database to create an idealized "1 in 50 year" cyclone event, which is then used to force a physics-based numerical storm surge model to predict the extreme water-level at the coast (e.g. Jain et al., 2010a; Rao et al., 2010). Five cyclone parameters are used to determine the wind and pressure fields within the Jelesnianski and Taylor (1973) idealised cyclone model, and are important to storm surge generation (e.g. Azam et al., 2004; Resio and Westerink, 2008). These are: (1) the radius of maximum winds (RMAX), which is also

called storm size; (2) pressure drop ($\Delta$P), calculated as the difference between a cyclone's central pressure (CP) and the ambient pressure (we assume 1010hPa); (3) cyclone track speed (mvspeed); (4) cyclone track (hence landfall location), and (5) the cyclone bearing during landfall, which is called the angle of attack to the coast.

[4] Each of these parameters is subject to natural variability even for storms of the same recurrence interval. For example, the estimated extreme pressure drop ($\Delta$P) of the "1 in 50 year" cyclone has varied widely in three recent Bay of Bengal extreme water-level estimation studies: (1) 66 hPa, based on analysis of cyclones in a small region of interest (Rao et al., 2010); (2) between 66 hPa and 94 hPa, dependent upon the region of interest (Jain et al., 2010a); (3) 68.7 hPa, based on the analysis of cyclones throughout the Bay of Bengal (Sindhu and Unnikrishnan, 2011). However, the impact of such natural variability in cyclone parameters on flood hazard has yet to be quantified. Therefore, the purpose of this paper is to understand the effect of the natural variability within these five key cyclone parameters to determine the likely uncertainty in Bay of Bengal flood risk estimates.

## 2. METHODOLOGY

[5] The characteristics of key cyclone parameters ($\Delta$P, RMAX, VMAX, mvspeed, angle of attack) were analysed using the IBTrACs (version 2) dataset (http://www.ncdc.noaa.gov/oa/ibtracs/, 2010). The Willoughby et al. (2006) equation (1) was used to estimate the radius of maximum winds (RMAX), using parameters of maximum wind speed (VMAX) and latitude ($\psi$), because observations of RMAX were not available within version 2 of IBTrACs.

$$RMAX = 46.4*\exp(-0.0155*VMAX+0.0169*\psi) \quad (1)$$

[6] Sixty-six storm events that had a full dataset and made landfall (as a cyclone) in the Bay of Bengal were identified between 1950 and 2008. Tropical storms (weather systems

with wind speeds less than 64 knots, based on the Saffir/Simpson scale), are likely to behave differently to the cyclone events that cause serious coastal inundation; therefore, tropical storms were removed from further analysis if VMAX was less than 64 knots during the 12 hour period before landfall. The natural variability and the spatial dependence (with landfall zone) of the key cyclone parameters were determined from the remaining 18 observed Bay of Bengal cyclone events. The statistical variation based on these analyses was then used to force idealised cyclone models and propagated through a storm surge model (IIT-D) in a series of sensitivity tests. The landfall location of cyclone *Sidr* was central to these tests because the largest historical storm surges are generated from cyclone landfall in this region (see As-Salek, 1998); also, a LISFLOOD-FP inundation model has been validated for the cyclone Sidr event (see Lewis et al., 2012), which allows us to propagate storm surge uncertainty through to predicted inland inundation extent.

## 3. 1. SPATIAL SIMILARITY OF CYCLONE PARAMETERS AND NORMALITY OF DATA

[7] The spatial similarity of four cyclone parameters (ΔP, RMAX, VMAX, mvspeed), and cyclone development characteristics (δRMAX.δt and δCP.δt), were tested using the Kolmogorov-Smirnov goodness-of-fit hypothesis test, based on four landfall regions: (1) Far West (~Southeast India) 75-80.85°E, (2) Central West (~Northeast India) 80.85-86.35°E, (3) Central East (~Bangladesh) 86.35-92.20°E and (4) Far East (~Myanmar) 92.20-100°E. The 18 observed cyclone tracks and the four landfall regions are shown in Figure 1. The regions were delimited based on a number of previous studies (e.g. Rao et al. 2010; Jain et al. 2010a), but modified to give a similar sample size (*n* between 4 and 5). With this sample size, cyclone parameters from the four different sub-regions were found to be similar (at a 95%

significance level). We conclude that it is reasonable to pool cyclone parameters for the Bay of Bengal, irrespective of landfall location. A Lilliefors' test showed a normal distribution for each cyclone parameter (from the 18 events), with the exception of the radius of maximum winds (RMAX), which was estimated (equation 1). Therefore, observations from all cyclone events in the Bay of Bengal can be used to characterise the natural variability of cyclone parameters assuming a normal distribution.

## 3.2. NATURAL VARIBILITY WITHIN THE IDEALISED 1 IN 50 YEAR CYCLONE PARAMETERS

[8] A "1 in 50 year cyclone event" is the usual basis for flood risk modelling in this region (e.g. Jain et al., 2010b), and, as cyclone parameters are similar throughout the Bay of Bengal, the Sindhu and Unnikrishnan (2011) 50-year extreme $\Delta P$ estimate can be used (68.7 hPa) as the basis of an idealised cyclone event. Hence, by cascading observed variability within key cyclone parameters through the storm surge model, the storm surge uncertainty associated with this idealized 1 in 50 year cyclone event can be investigated.

[9] The cyclone wind-pressure relationship is actually a function of several factors relating to an individual cyclone's environment and structure (Knaff and Zehr, 2007). Furthermore, there is no way to prescribe wind speed uncertainty into most cyclone storm surge models because it is estimated within the idealised cyclone model for computational stability (see Jelesnianski and Taylor, 1973). Indeed, the variability within the wind-pressure relationship can be seen in Figure 2. However, when considering RMAX and latitude ($\psi$) uncertainty within the Jelesnianski and Taylor (1973) VMAX approximation (J-T range), we see the variability within the wind-pressure relationship is greater based on a linear regression (2) for the 18 cyclone events ($R^2$ of 81%, Spearman rank of 0.88 and $P > 0.01$). Moreover,

this observed wind-pressure variability (see data points of Figure 2) is much greater than the differences between three typical Indian Ocean wind-pressure relationships (equations 3, 4 and 5; see Ozceluk et al., 2012). Therefore, based on our results, the natural variability with VMAX is much greater than the uncertainty of prescribing the wind-pressure relationship in an idealised cyclone model.

$$VMAX = 0.4*\Delta P + 30.45 \quad (2)$$

$$VMAX = 3.44(\Delta P\text{^}0.644) \quad (3)$$

$$VMAX = 6.3(\Delta P\text{^}0.5) \quad (4)$$

$$VMAX = 7(\Delta P\ \text{^}0.5) \quad (5)$$

[10] To prescribe the natural variability of VMAX within a 50-year cyclone event, we can reverse the linear regression of the wind-pressure relationship (2). Furthermore, we can include 68% of the natural variability we see in the wind-pressure relationship of Figure 2, with one standard deviation (s.d) of the linear wind-pressure relationship (2), either side of the 50-year extreme ΔP estimate (68.7 hPa). The storm surge response to this 50-year ΔP uncertainty range (which now includes VMAX uncertainty) can be simulated if a cyclone track and RMAX are also synthesised. Uncertainty within the RMAX of a 50-year cyclone event can be represented by propagating the estimated VMAX range through equation 1, assuming constant latitude ($\psi$) of 15.5°N (the average latitude from the 18 observed cyclone events). Furthermore, the storm surge response to uncertainty within each of the key idealised parameters (for a 1 in 50 year cyclone event) can be tested by holding all other cyclone parameters at a “standard” 50-year value, and propagating an appropriate uncertainty range through the storm surge model; see Table 1.

[11] Extreme water-level estimate studies typically use observed tracks (e.g. Jain et al., 2010a; Rao et al., 2010); however, a cyclone track can be synthesised by propagating the angle of attack (mean ± s.d.) outward from the coastline for 18 hours (the typical duration of

angle of attack observed) and connecting this position to an assumed cyclone genesis location. Two genesis locations (a “standard” central Bay of Bengal location at 87.5°E 10°N, and the cyclone *Sidr* genesis location: 93.2°E 9.6°N) were assumed for our genesis sensitivity test. The mean angle of attack (cyclone bearing during landfall) was calculated from the 10 events observed in zones 2 and 3 of Figure 1, and the associated standard deviation either side of this “standard” value was used for the angle of attack range in the sensitivity test (see Table 1). The cyclone *Sidr* landfall location was chosen (89.76°E 21.75°N) as the “standard” for our sensitivity test, with the position varying by 26 km (the average coastal spacing between landfall locations from the 18 observed events) for sensitivity test B (see Table 1).

[12] No relationship between cyclone track speed (mvspeed) and cyclone strength ($\Delta P$) was found for the 18 observed cyclone events; however, the average track speed was different before and after cyclone landfall. Therefore, a “standard” time-series (6 hour time-step) of the cyclone position was determined assuming a central genesis location and the average mvspeed pre and post-landfall. The uncertainty of mvspeed was assumed to be represented by ± one standard deviation (s.d.) of the mvspeed variance; see test E in Table 1. Lastly, to synthesise a time-series (6 hourly) of pressure drop ($\Delta P$) and storm size (RMAX) for the storm surge model, the mean development (genesis to peak cyclone value) and attenuation rates (decay of parameter after landfall) were calculated (from the 18 observed events) for a “standard” case (assuming the peak value occurs for 10% of cyclone duration before landfall). The sensitivity test of cyclone development (and attenuation; see test D in Table 1) was constructed by including ± one s.d. within the mean development and attenuation characteristics of RMAX and $\Delta P$ (see Table 1).

## 3.3. STORM SURGE UNCERTAINTY WITHIN AN IDEALISED 1 IN 50 YEAR CYCLONE.

[13] Storm surge uncertainty associated with this idealized 1 in 50 year cyclone event making landfall at 89.76°E and 21.75°N (cyclone *Sidr* landfall location) was investigated by individually cascading 68% of the calculated variability (for 18 events) through the storm surge model for seven cyclone parameters (hence 14 model runs in total; see Table 1). Surprisingly, storm size (RMAX) uncertainty and the uncertainty within cyclone development characteristics (δRMAX.δt and δP.δt) did not affect the magnitude of simulated peak storm surge. However, such a result should be viewed with caution because of the assumptions made and the absence of timing (e.g. tide-surge) interactions in the model.

[14] The uncertainty within the estimated storm surge was found to be very high. Cyclone strength (ΔP) was found to have the greatest effect upon storm surge height. Cyclone track uncertainty (genesis location, landfall and mvspeed) were also shown to have a significant effect to simulated storm surge magnitude (see Table 1); however, the sensitivity of storm surge along the coastline can be affected by cyclone parameter choice (see Azam et al., 2004). Furthermore, the estimated uncertainty within angle of attack significantly altered storm surge height distribution along the coastline (see Figure 3). Whilst the peak cyclone parameter uncertainty (ΔP and RMAX) generated the greatest storm surge difference, the spatial distribution of the peak storm surge may be very important for estimating coastal flood hazard (Figure 3).

[15] The simulated storm surge uncertainty (see Figure 3) was propagated into the LISFLOOD-FP inundation model of Lewis et al. (2012), assuming a mean spring tide sinusoidal time series interpolated along the northern Bay of Bengal coastline. The inundation difference of the peak cyclone parameter uncertainty within the idealised “1 in 50 year” cyclone event was calculated as 279 $km^2$ (test G of table 1), whilst uncertainty within the coincidence of the storm surge and tidal peaks (i.e. maximum surge height at low water or

high water) resulted in a bigger inundation difference of 441 km². The largest inundation difference of 1179 km² was simulated for the angle of attack sensitivity test (test C of Table 1). Therefore, uncertainty in inundation extent calculations arises from several factors, and characterising the natural variability within an idealised extreme cyclone event is essential for robust extreme water-level and flood risk estimates.

## 4. SUMMARY

[16] Extreme cyclone parameters within the Bay of Bengal have no relationship with landfall location and are normally distributed. Therefore, the entire Bay of Bengal cyclone observation record can be used to characterise the natural variability within extreme cyclone parameters. Uncertainty within the parameters used to simulate a “1 in 50 year” cyclone was found to be high, and led to considerable differences in simulated storm surges (of the order of metres). Furthermore, not all uncertainty was propagated through the storm surge model (e.g. tide-surge interaction, air-sea drag coefficient uncertainty and only 68% of observed natural variability within a small sample size). The simulated storm surge uncertainty from an idealised “1 in 50 year cyclone event” resulted in large differences in simulated inundation extent. Therefore, a Joint Probability Method (JPM) of cyclone extreme water-level estimation (e.g. Irish et al., 2011; Resio et al., 2009) may be a better approach to extreme water-level estimation in regions such as the Bay of Bengal, because multiple cyclone parameters are then statistically combined.

[17] The finding that the natural variability within storm size (RMAX) had no significant effect on the simulated storm surge magnitude is doubtful; especially when considering the importance of cyclone parameter uncertainty within inundation modelling of hind-cast events (see Lewis et al., 2012; Madsen and Jakobsen, 2004). Therefore, future work

should try to obtain a longer cyclone parameter record with more storm size (RMAX) observations (i.e. the recently released IBTrACs version 3). Certainly the uncertainty of storm surge response to natural variability of cyclone parameters requires further investigation before robust extreme water-levels are made for the Bay of Bengal. Furthermore, future work should investigate flood risk uncertainty due to wave set-up and tidal contributions (see Jain et al., 2010b; Sindhu and Unnikrishnan, 2011), inundation modelling uncertainties (e.g. roughness and DEM uncertainty; see Lewis et al., 2012), and projected future changes to the extreme water-level climate (see Karim and Mimura, 2008). However, the work presented here indicates that robust extreme water-level estimates for the Bay of Bengal (which include natural variability) should be a priority. Furthermore, in addition to inundation risk analysis (as here) the statistical variance of cyclone parameters could be used to generate a computationally-efficient short term ensemble forecast for flood warning and evacuation.

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**Figure Captions:**

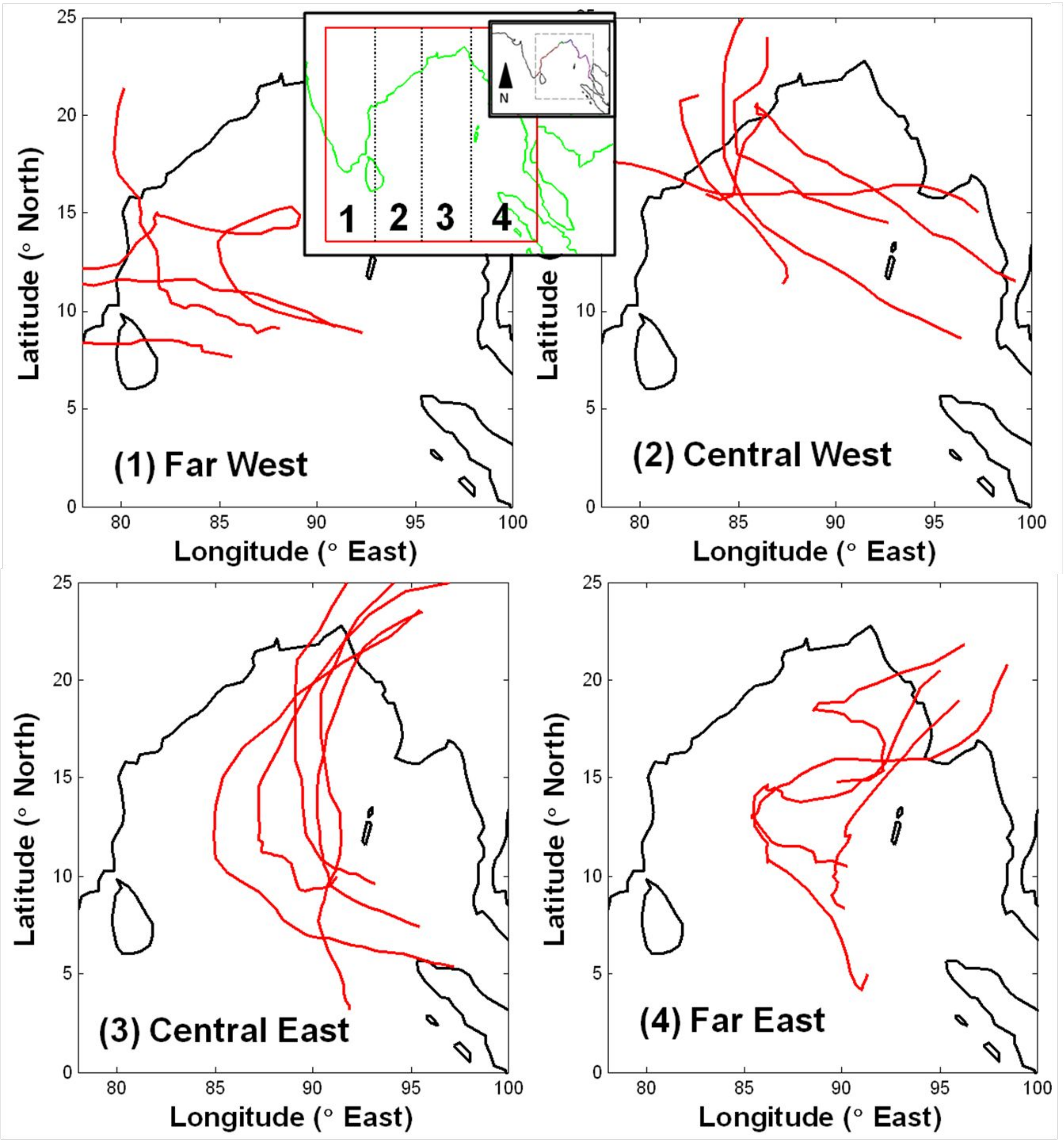
Figure 1: The tracks of 18 cyclone events observed between 1990 and 2008, separated into four landfall regions of the Bay of Bengal: (1) Far West 75-80.85°E, (2) Central West 80.85-86.35°E, (3) Central East 86.35-92.20°E and (4) Far East 92.20-100°E.

Figure 2: The observed variability within the cyclone wind-pressure relationship from 18 events (gray shaded region of equation 2), compared to three methods of VMAX approximation (equations 3, 4 and 5) and the Jelesnianski and Taylor (1973) wind pressure approximation (J-T range). The potential pressure drop (ΔP) uncertainty associated with the natural variability of VMAX for a 68.7hPa cyclone is shown with an arrow, which is greater than the uncertainty range from the J-T range and equations 3, 4 and 5).

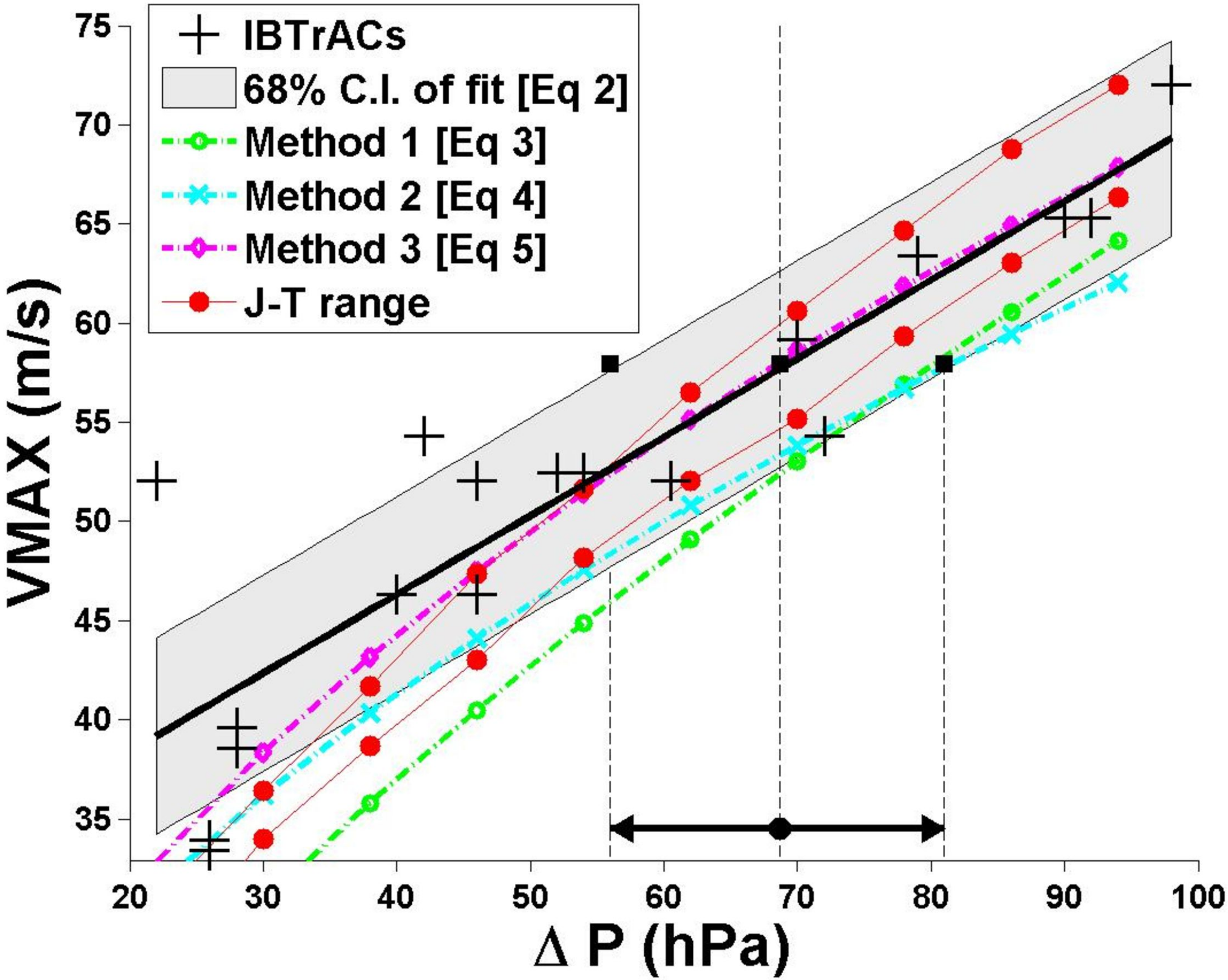
Figure 3: Storm surge height along Northern Bay of Bengal coastline (km), due to natural variability of key cyclone parameters for a “1 in 50 year” cyclone (assuming cyclone Sidr landfall) for: cyclone genesis position (A), landfall location variation around the 2007 Sidr landfall position (B), angle of cyclone attack to the coastline (C), cyclone track speed (E)

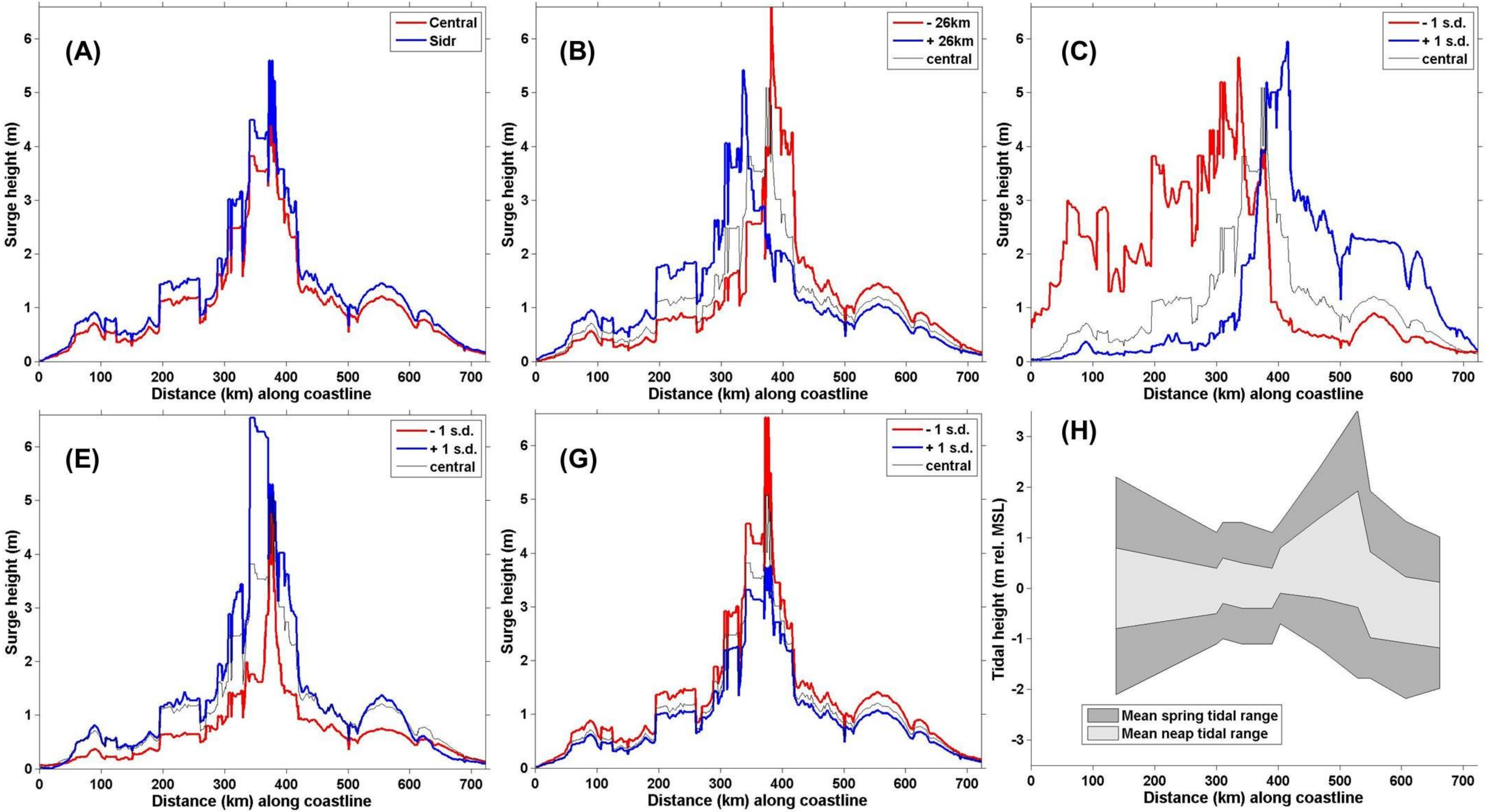
and peak cyclone strength variation ($\Delta$P uncertainty; G), which is compared to the interpolated average admiralty tidal range along the coastline (H). Cyclone development (D) and radius of maximum wind (F) sensitivity tests were omitted from this figure because no storm surge difference was simulated (hence will have the same surge response as “central”).

| Test | Cyclone parameter sensitivity test | Standard value assumed | Assumed variability of cyclone parameter | | Peak storm surge difference (m) |
|---|---|---|---|---|---|
| A | Genesis | 87.5°E 10°N (central) | 93.2°E 9.6°N (*Sidr*) | 87.5°E 10°N (central) | 0.51 |
| B | Landfall | 89.76°E & 21.75°N | ±26km of standard landfall position | | 0.89 |
| C | Angle of attack | 347°N | 291°N | 43°N | 0.07 |
| D | ΔP.∂t (pre and post landfall) | 0.5hPa/hr and -1.67hPa/hr | 0.67 and -3.00 hPa/hr | 0.33 and -0.34 hPa/hr | 0.00 |
| | RMAX.∂t (pre & post landfall) | -0.17km/hr and 1.17km/hr | -0.34 and 2.00 km/hr | 0 and 0.34 km/hr | |
| E | Mvspeed (m/s) pre and post landfall | Pre; 3.8m/s post; 6.7m/s | 4.8 and 9.8m/s | 2.8 and 3.6m/s | 1.39 |
| F | Peak RMAX | 25km | 23km | 27km | 0.00 |
| G | Peak ΔP | 68.7 hPa | 56.2 hPa | 81.2 hPa | 2.77 |



(1) Far West
(2) Central West
(3) Central East
(4) Far East
1
2
3
4
N
Latitude (° North)
Longitude (° East)


IBTrACs
68% C.I. of fit [Eq 2]
Method 1 [Eq 3]
Method 2 [Eq 4]
Method 3 [Eq 5]
J-T range
VMAX (m/s)
Δ P (hPa)
75
70
65
60
55
50
45
40
35
20
30
40
50
60
70
80
90
100



(A)
Central
Sidr
(B)
- 26km
+ 26km
central
(C)
- 1 s.d.
+ 1 s.d.
central
(E)
- 1 s.d.
+ 1 s.d.
central
(G)
- 1 s.d.
+ 1 s.d.
central
(H)
Mean spring tidal range
Mean neap tidal range
Surge height (m)
Tidal height (m rel. MSL)
Distance (km) along coastline